ATONOMETRICS

The Effects of Soiling on PV Performance
A Brief Literature Survey

In this white paper we give a brief survey of the published literature on the effects of soiling on PV module and array performance. The studies reviewed show that soiling is a major factor in the performance of PV installations, and also that it is highly dependent upon weather conditions and geographic location.

PV Module Soiling Measurement Methodology

The generally accepted methodology for measuring PV module soiling is to measure the ratio of the electrical outputs of a clean and dirty PV device. This methodology has been used since at least 1989 [1]. Often, measurements are made on the same device before and after cleaning, but for data to be collected continuously, side-by-side measurements of a clean and dirty device should be made simultaneously.

Accumulated Soiling Losses and Soiling Rates

PV Module Soiling at the PVUSA Site in Davis, California

In 2000, engineers from Endecon Engineering published a study of data collected at the PVUSA test site in Davis, California. In their study they measured annual soiling losses as high as 7%, and monthly soiling losses as high as 20% [2]. The authors also published recommended monthly soiling loss profiles at the PVUSA site for a "wet", "dry", and "normal" year. Their recommendations are summarized in Figure 1, reproduced from the paper and shown below:

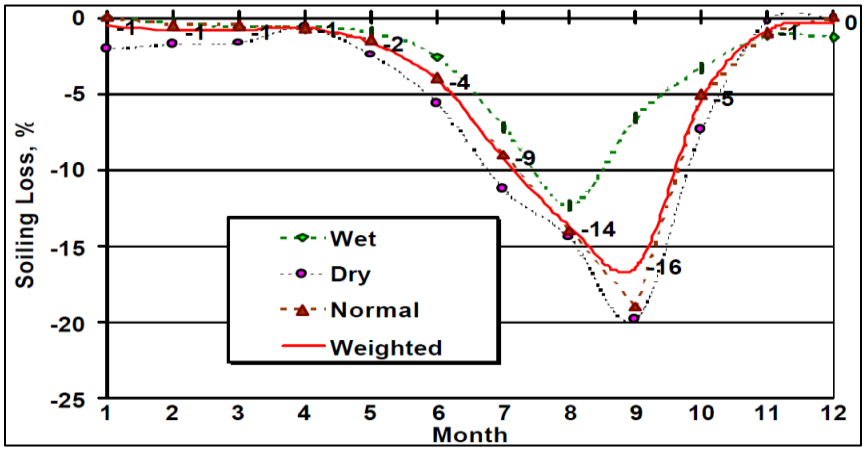

Figure 1: Recommended monthly soiling loss profiles for a "wet"(green diamonds), "dry" (purple circles), and "normal"(red triangles) year at the PVUSA site in Davis, California, published in Ref. [2].

The Effects of Soiling on Utility Scale PV Systems in Arizona and California

In 2006 PowerLight Corporation published a study of the effects of soiling on 10 PV systems for the 2005 calendar year [3]. The PV systems were distributed among urban and rural environments in the California Central Valley, Northern California, Southern California, and the US Desert Southwest. The authors measured annual soiling losses to be as large as 6%, and hourly soiling losses to be greater than 20% [3]. The authors also found that without rainfall measured PV efficiencies declined 0.1% to 0.3% per day due to soiling, with an average soiling degradation rate of 0.2% per day in dry climates [3].

The Effects of Soiling on First Solar Frameless CdTe Modules in California

Caron and Littmann from First Solar recently published a study of the effects of PV module soiling on First Solar CdTe PV Modules in California [4]. They measured soiling rates of less than 1% per month in desert environments in California, "peak" soiling rates of 11.5% per month in "heavy agricultural regions of the Central Valley," and total monthly soiling losses approaching peak values of 9% [4]. The authors were also able to correlate experimentally measured PV module soiling with the normalized performance of a First Solar PV array located 35 km away from their soiling measurement experiment. The results are shown below in Figure 3, which is reproduced from their work:

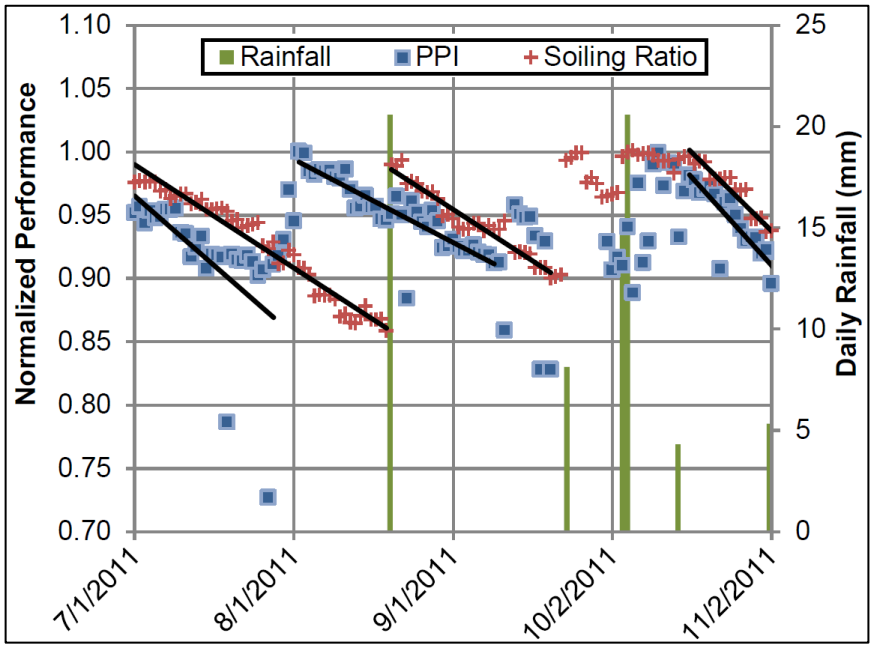

Figure 2: The left y-axis shows experimentally measured PV module soiling ratios (red "+" marks), overlaid with normalized PV array performance at a site located 35 km away from the soiling experiment (blue squares). The right y–axis shows daily rainfall in mm (green bars). The improvement in PV array performance shown on 8/1/2011 was due to manual PV array cleaning. Other PV array performance improvements and decreases in PV module soiling shown are correlated with rainfall.

AlBusairi recently published results showing monthly yield losses due to Soiling of First Solar modules in Kuwait to be greater than 24% [5].

Daily Soiling Values Measured at the University of Málaga

Zorilla-Casanova and his co-authors have also published an illuminating depiction of PV module soiling loss over time at their site in Málaga, Spain [6]. We reproduce a graph here taken from Ref [6], adding dashed lines to guide the eye in order to illustrate different soiling rates over time. It is obvious that Daily Soiling Losses approach 25%.

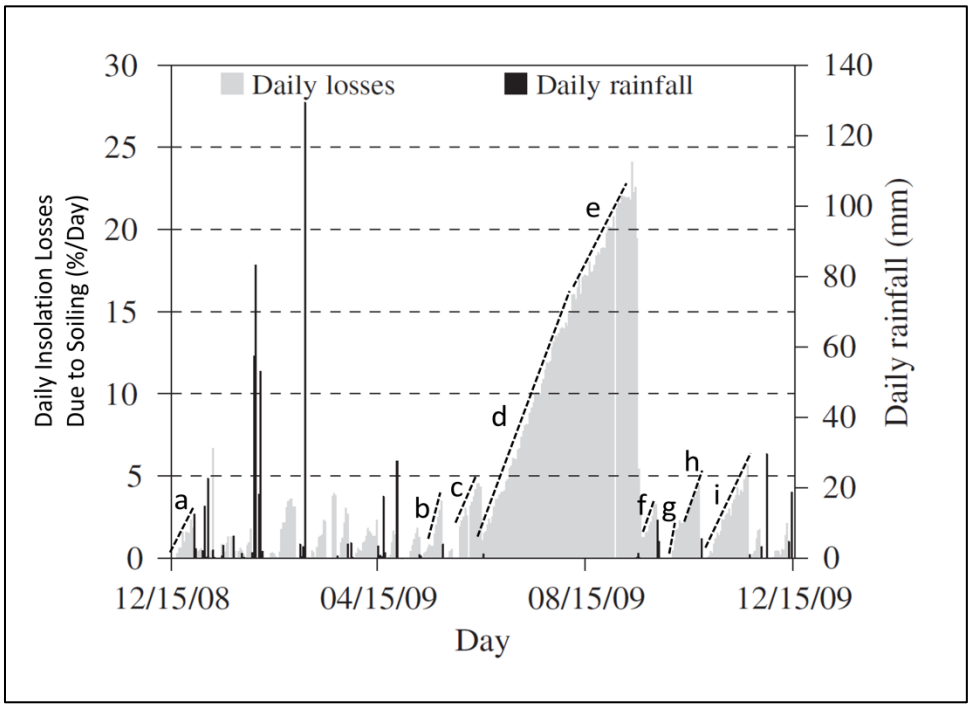

Figure 3: Daily Lost Insolation Due to PV soiling in %/day (light vertical bars – right y-axis), and daily rainfall in mm (dark vertical bars – left y-axis). Dashed lines showing the average rate of increase of PV module soiling have been added to guide the eye. The rate of soiling increase corresponding to each lower case letter is shown in Table 1.

In Figure 3 we have added dashed lines to illustrate the approximate rate of increase of PV soiling over time for different periods. Each separate discrete rate of increase has been labeled with a lower case letter. In Table 1 we include a legend in which the approximate rates of soiling increase have been calculated. The rate of increase of daily lost insolation varied from 0.20%/day/day to 0.55%/day/day.

Table 1: Rate of Soiling Loss Increases Shown in Figure 3

Label	Soiling Rate (% Insolation Lost/Day/Day)
a	0.20%
b	0.39%
c	0.24%
d	0.28%
e	0.20%
f	0.30%
g	0.55%
h	0.29%
i	0.22%

Soiling as a Function of Solar Angle of Incidence

Zorrilla-Casanova *et. al* recently published a detailed study of the effects of dust accumulation on PV performance at the University of Málaga in Málaga, Spain [7]. The authors reported soiling losses measured in real time as high as 30%, and daily irradiance losses over 21%. The authors were able to show the functional form of PV soiling loss as a function of angle of incidence of the sun. Those results are summarized below in Figure 2, reproduced from the paper and shown below:

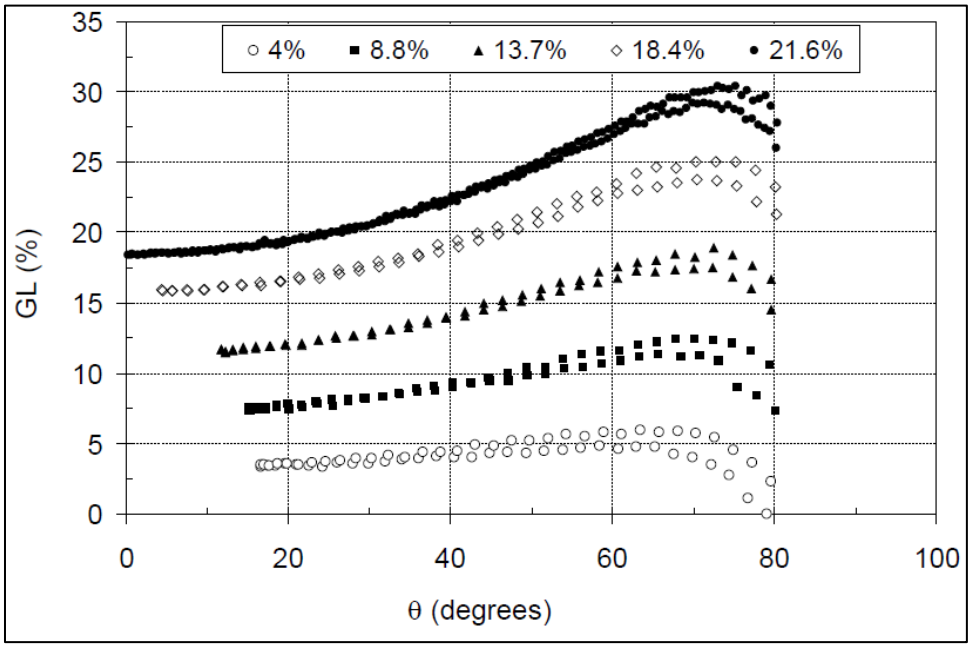

Figure 4: Soiling loss as a function of solar angle of incidence for several different days. The term "GL" indicates the relative irradiance loss due to soiling. The legend at the top of the graph indicates the average daily lost irradiance for each curve.

Importantly, the authors measured the effects of soiling with PV reference cells, eliminating the possibility of measuring additional effects due to non-uniform soiling of PV module. Irradiance nonuniformity can have a large impact on PV module performance [8], and non-uniform soiling has been clearly documented in the literature [9].

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